Numerical Modeling of Atmospheric Re-entry Environment for TPS Design

Abhilasha Anna, Iain D. Boyd

NGPDL, University of Michigan

MOTIVATION

- Hypersonic vehicles experience aerodynamic heat loads:
  - Cause very high temperatures on their surface
  - Use Thermal Protection System (TPS)
  - Prolonged exposure to high temperature and chemical reactions can cause TPS to fail
- Depending on the heat load
  - Ablative TPS (eg. Stardust)
  - Non-ablative TPS (eg. Space shuttle)
- Surface heating affected by:
  - Catalycity of the TPS material
  - Chemical reaction between the surface material and boundary layer gases ⟶ surface recession

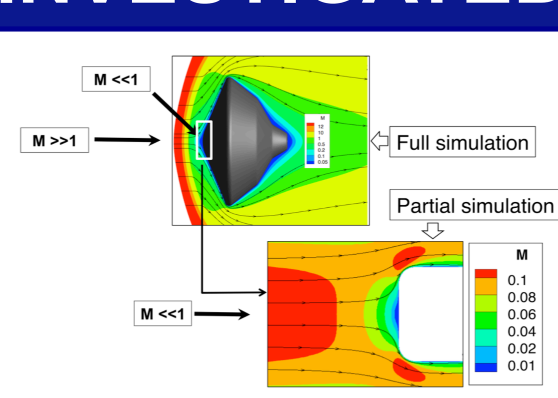
Accurate modeling of these gas-surface interactions is necessary for the prediction of aerothermal heating of the vehicle TPS

OBJECTIVES

- Investigate surface chemistry models to describe dominant gas-surface interaction processes (e.g. catalysis, nitridation) implemented in a CFD code.
  - current study is an extension to previous studies (AIAA-2012-534, RTO-AVT-199-2012, AIAA-2013-0187)
  - gas-surface interaction model used (surface catalysis and surface participating reactions eg. nitridation, oxidation)
  - Gas considered: Pure Nitrogen
  - physical accuracy of the computational results assessed using experimental data generated in high-enthalpy facility at the University of Vermont (UVM)
  - sensitivity analysis of the free stream chemical composition performed

FLOW DOMAIN INVESTIGATED

Entry flight environment considered: Post shock subsonic high enthalpy gas flow



TECHNICAL APPROACH

- **Computational Tools:** LeMANS: CFD code developed at the University of Michigan (Scalabrin and Boyd: AIAA-2006-3773)
  - solves laminar Navier-Stokes equations
  - can account for thermo-chemical nonequilibrium effects
  - finite volume algorithm with point/line implicit time integration
  - 2D/3D/Axisymmetric simulations on structured/unstructured grids
  - parallelized using domain decomposition

TECHNICAL APPROACH

- **Species boundary conditions**
  - finite rate surface chemistry (FRSC) model (Maclean & Marshall 2011, Alkandry et. al 2012): surface catalysis and surface participating reactions (eg. nitridation, oxidation)
  - Gas-surface interaction processes studied:
    - recombination of N atoms to molecules at the surface due to catalysis
    - carbon nitridation: N atoms react with the surface carbon to form gaseous CN
  - FRSC model used to simulate a constant reaction efficiency γ

1) $N+(s)\rightarrow N(s)$: Adsorption ($E_{ad}=0$ J/mol)

$N+N(s)\rightarrow N_2+(s)$: Eley-Rideal recombination ($E_{ER}=0$ J/mol)

$$\gamma=\frac{2S_0\gamma_N}{S_0+\gamma_N}$$

2) $N+(s)\rightarrow N(s)$: Adsorption ($E_{ad}=0$ J/mol)

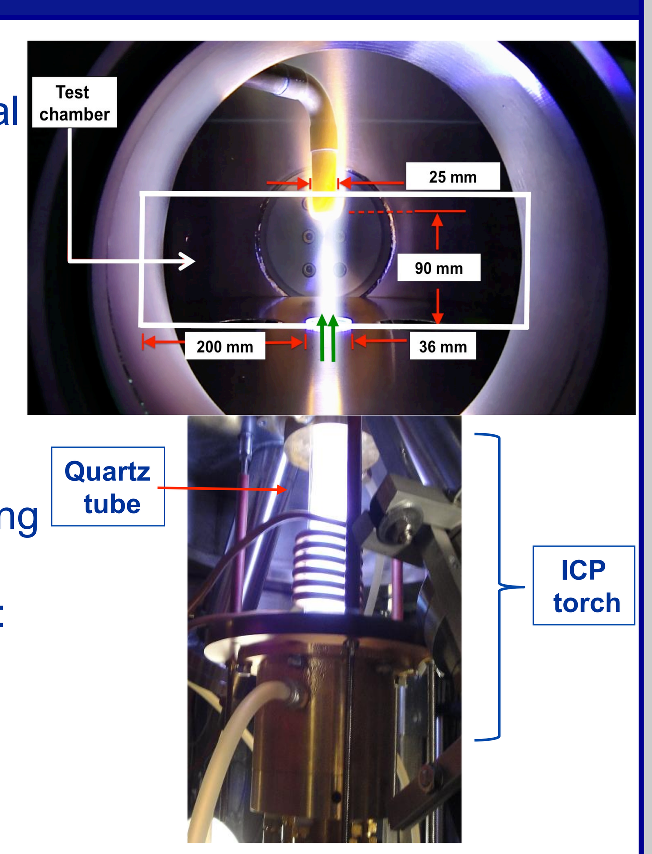
$N+N(s)\rightarrow N_2+(s)$: Eley-Rideal recombination ($E_{ER}=0$ J/mol)

$C_b+N+(s)\rightarrow CN+(s)$: Eley-Rideal recombination ($E_{ER}=0$ J/mol)

$$\gamma=\frac{2S_0\gamma_N+\gamma_{CN}\gamma_N}{S_0+\gamma_N}$$

ASSESSMENT OF COMPUTATIONS

- Assessment of simulations performed using experimental tests at UVM
  - 30 kW Inductively Coupled Plasma (ICP) Torch Facility
- Samples exposed to high enthalpy subsonic gas flows
- Flow quantities measured using two-photon Laser Induced Fluorescence (LIF) technique:
  - Relative N-atom number density
  - Translational temperature
- Surface temperature and sample ablation also quantified



Graphite sample in nitrogen flow (section in box is the portion simulated)
Source: Prof. D.G. Fletcher (UVM)

NUMERICAL SETUP

- Free stream values and wall temperature based on experimental setup

Mass flow rate [kg/s]	T_∞ [K]	P_∞ [kPa]	T_W [K]
0.82 x 10^{-3}	7000	21.3	1598

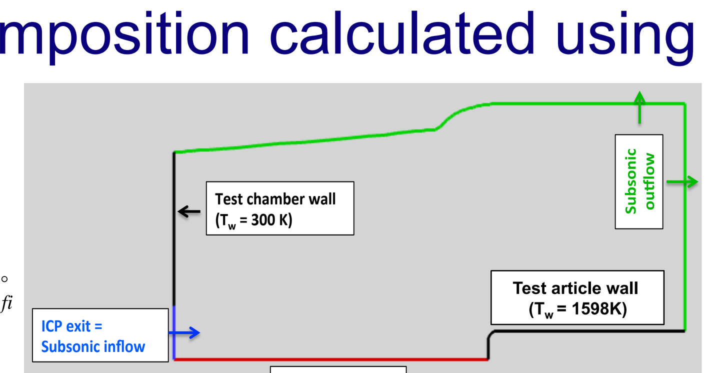
- Inlet chemical composition calculated using

(i) Chemical Equilibrium with Applications (CEA)

(ii) Power $=\dot{m}\Delta h$

$$\Delta h=\sum_{i=N,N_2} Y_i\int_{298}^{T} C_{pi}\,dT+\sum_{i=N,N_2} Y_i\Delta h_{fi}^{o}$$

Inlet Power $\approx 13.8kW$



Boundary conditions

- Flow physics model: Thermochemical nonequilibrium
- Radiative equilibrium
- Grid generated: Pointwise
  - 22,000 quadrilateral cells

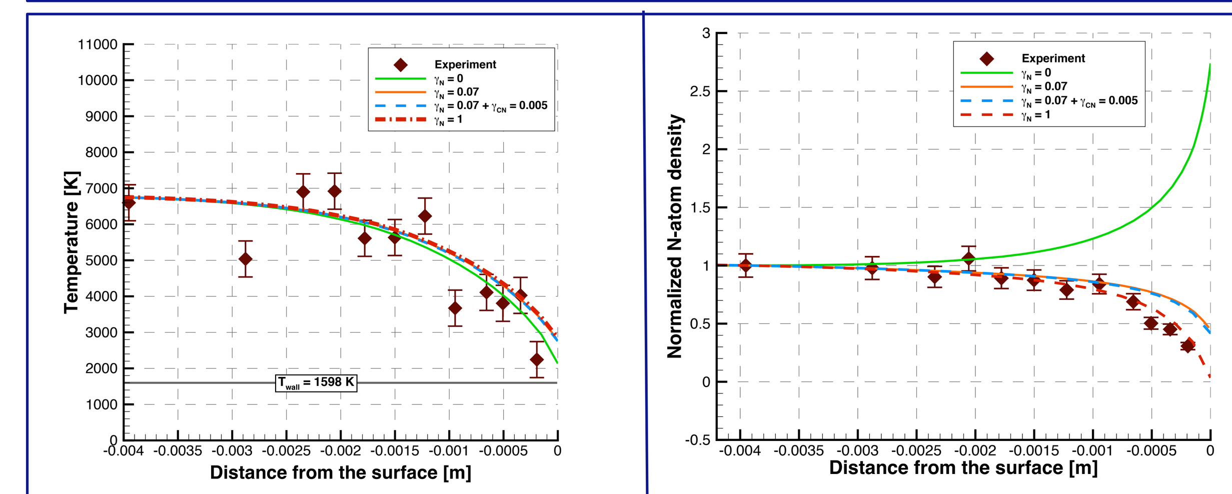
Acknowledgments

- AFOSR Grant FA-9550-11-1-0309
- Prof. Doug Fletcher and his graduate students, University of Vermont

RESULTS

Comparison with Experimental Data

Axial profiles next to surface

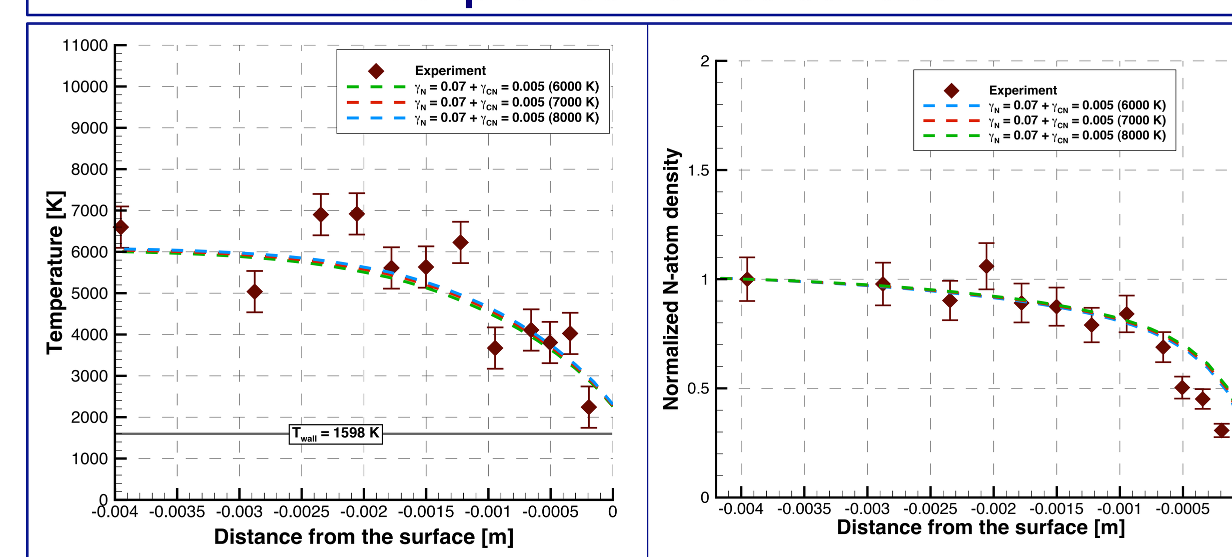


Translational temperature — Normalized N-atom density

inlet composition	T_∞ [K]	q_{stag} [W/cm²]	T_{stag} [K]	mass loss rate [kg/s]
CEA	7000	270.415	2757.542	2.213
13.8 kW	7000	127.783	2284.063	0.861

Sensitivity to Inlet Temperature (Power = 13.8 kW)

Axial profiles next to surface

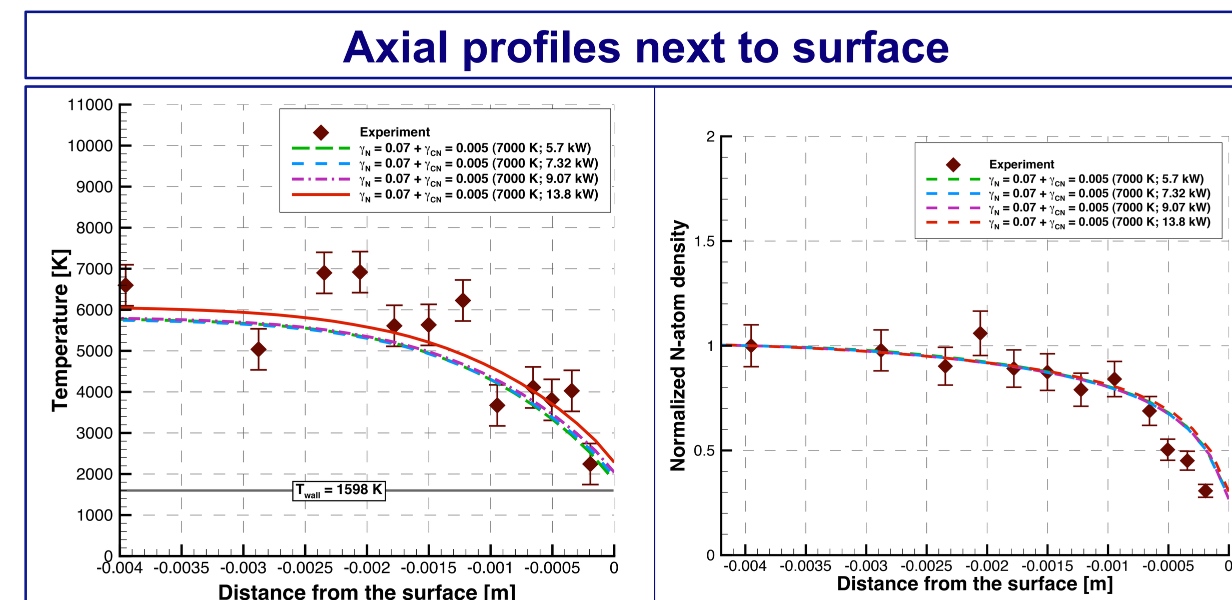


Translational temperature — Normalized N-atom density

Power [kW]	T_∞ [K]	q_{stag} [W/cm²]	T_{stag} [K]	mass loss rate [kg/s]
13.8	6000	122.258	2258.888	0.831
13.8	7000	127.783	2284.063	0.861
13.8	8000	133.198	2307.974	0.899

Sensitivity to Inlet Power

Axial profiles next to surface



Translational temperature — Normalized N-atom density

Power [kW]	X_N	T_∞ [K]	q_{stag} [W/cm²]	T_{stag} [K]	mass loss rate [kg/s]
5.7	0	7000	51.856	1820.910	0.113
7.3	0.1	7000	65.953	1934.392	0.265
9.1	0.2	7000	81.662	2041.070	0.422
13.8	0.423	7000	127.783	2284.063	0.861
Experiment		~7000	40 - 80	~ 1600	0.2 – 0.6

CONCLUSIONS

- Temperature in the boundary layer not affected by different surface reactions
- Nitrogen atom density decreased when surface chemistry was included
- Carbon mass loss, stagnation temperature and heat flux
  - decreased significantly for chemical composition calculated using inlet power as opposed to the equilibrium composition calculated using CEA
  - not significantly sensitive to inlet temperature
  - significantly sensitive to inlet power